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Coastal vulnerability index for the indented coastline of Primorje-Gorski Kotar County, Croatia

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ABSTRACT

The study explores the general vulnerability of the coastline, with a focus on assessing vulnerability using the coastal vulnerability index (CVI) along the highly indented coastline of Primorje-Gorski Kotar County (PGC), Croatia. Vulnerability was assessed every 25 m of the 1235 km long coastline by calculating the CVI based on five representative variables: geological setting, coastal slope in relation to terrain instabilities (rockfalls and landslides), significant wave height, coastal flooding, and beaches, which were also integrated into a single overall CVI. The length of the coastline, characterised by different relief forms, and the scale of available data required an adaptation of the commonly used methodology. The results show a low overall vulnerability, mainly due to the prevalence of relatively resistant carbonate sedimentary rocks along the coasts. However, almost a quarter of the investigated coastline is highly or very highly vulnerable to coastal flooding. Of particular concern is the fact that many of the most vulnerable areas are inhabited. Analyses at this scale are suitable for regional spatial planning. The results of the conducted research are available publicly online, which enables their practical application for planning and management of coastal areas. Adaptation to the impacts of climate change is highly dependent on the location itself, but overall, this assessment provides indications of the most vulnerable locations in the PGC, where it is necessary to limit interventions in the coastal area.

1. Introduction

Coastal areas are dynamic and complex environments that form the interface between land and sea and play a central role in ecological, social, and economic systems. However, they are increasingly exposed to a range of hazards, including storm surges, coastal erosion, saltwater intrusion, and habitat degradation, all of which are exacerbated by climate change and human activities (IPCC, 2023). The UNDP (2009) emphasizes the importance of understanding the implications of potential future sea level changes for coastal spatial planners, managers and development officials as they establish regulations for coastal land use, disaster risk management and planning for major infrastructure projects (e.g. transportation, wastewater and/or water supply systems, etc.). As sea levels continue to rise and climate patterns become more unpredictable, the vulnerability of natural and human systems in coastal regions increases. In general, vulnerability is defined as the propensity of the environment, people or property to be adversely affected. In interaction with the hazards and exposure of a system, it defines the level of risk required to decide on adaptation actions (IPCC, 2023; Peña-Alonso et al., 2017; Rocha et al., 2023). The IPCC defines risk as the potential for adverse consequences (losses), including their magnitude and the context in which these consequences are considered significant in different parts of coastal communities. As coastal risk assessments usually include an analysis of socio-economic developments as well (Rocha et al., 2023), the definition of risk level is more complicated when no official and reliable data are available, which is the case in PGC. Therefore, we decided to study and quantify only coastal vulnerability, which is the first crucial step for the implementation of effective strategies to improve resilience and sustainable development.

Coastal vulnerability assessments are based on a variety of methods (Kantamaneni, 2016; Peña-Alonso et al., 2017): index- or indicator-based methods, geographic information system -based decision support systems and dynamic computer models. In the index-based approach, coastal vulnerability is expressed by a one-dimensional coastal vulnerability index (CVI) without units of measurement. The methodology was first proposed by Gornitz in 1991, later modified by Thieler and Hammar-Klose (1999) and has since been used in many

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vulnerability studies around the world. Often these approaches are not immediately transparent, as the final index does not provide an understanding of the assumptions that led to its calculation (Šimac et al., 2023). A clear explanation of the methodology used is necessary to support the proper application of index-based approaches. Vulnerability assessment is based on the analysis of a single coastal section and the assignment of vulnerability levels based on the previously defined key variables. The number and typology of key variables should be adjusted depending on the characteristics of the research area (ETC CCA, 2011), as they often represent natural parameters that influence vulnerability. Different anthropogenic activities can increase or decrease vulnerability, so they can also be considered in the analysis. Finally, the CVI is applied as a cumulative index, i.e. it combines several variables through a quantitative or semi-quantitative assessment of each selected variable using different mathematical formulas. A detailed overview of the method based on the relevant literature can be found in the *Methodology* section. Different studies use different methodological approaches to apply the CVI at various spatial scales.

The CVI formulation based on the square root of the product mean of the vulnerability levels of the variables is most commonly used at the local, regional, and national scales. The U.S. Geological Survey (USGS) used this formulation to assess the potential vulnerability of the U.S. coast at the national level (Thieler and Hammar-Klose, 1999) and at the more detailed level of U.S. national park areas (Thieler, 2002). Specifically, the USGS examined and combined six variables: geomorphology, coastline erosion/accretion rates, coastal slope, relative sea level rise, mean significant wave height, and mean tidal range. The identical formulation of the CVI was applied to the coast of Mataram, on the island of Lombok (Indonesia) (Rudiastuti et al., 2020), covering 9 km of coastline, with 250 m long sections. The vulnerability of Andalusia was assessed with the same six variables, integrated into a single CVI with the same equation for the square root of the product mean (Ojeda Zújar et al., 2009). The authors analysed 200 m sections of a total of about 800 km of coastline. In later analyses of this coastal area, some parameters were replaced, such as the coastal slope parameter with a "topographic index" that expresses the mean value of the following three variables: mean elevation, mean slope, and area of inland penetration (Fraile Jurado, 2011).

Other authors have adapted the CVI to a particular coastal area or region as well, changing not only the number, but also the typology of key variables. For example, Abuodha and Woodroffe (2006) applied the CVI analysis to beaches in Australia, and CVI was adapted for this purpose with seven variables: dune height, barrier type, beach type, relative sea level change, erosion or shoreline accretion, mean tidal range, and mean wave height. The authors believe that dune height, barrier type and beach type are representative parameters for the Australian coast and the analyzed local vulnerability of the study area.

In the study on the coastal vulnerability of the Italian coast of the Apuglia region (Pantusa et al., 2018), four new variables were proposed in addition to the six previously described: beach width, dune width, vegetation width behind the beach, and the presence of *Posidonia oceanica* meadows. According to the authors, the newly proposed variables are representative of the Mediterranean coast and allow for the assessment of how natural systems gradually dissipate wave energy and thus reduce vulnerability. Sand dune systems provide a natural barrier that protects coastal areas from inundation by storm surges and wave action. Wide beaches and the presence of meadows of *Posidonia oceanica* have a positive effect on protecting the coast from erosion caused by wave action. The studied part of the Italian coast is divided into a series of sectors (beach cross-sections) with a width of 0.5 km. Tsaimou et al. (2023) investigated the vulnerability of a northeastern part of the Corinthian Gulf (central Greece) based on twelve variables. They emphasized the importance of a good segmentation of the coastline for the results to be representative of the area. However, their study area included six bays with coastlines between 0.3 and 1.88 km long.

Another study from western Greece studied a 100 km long coastal strip in a low-lying area struggling with significant erosion (Filippaki et al., 2023). The CVI was assessed using six variables defined by Thieler and Hammar-Klose and the aggregate index was calculated as the square root of the product mean, but the results were interpreted in relation to the land use of the area.

On the Greek Peloponnese peninsula, research on coastal vulnerability and sensitivity by Tragaki et al. (2018) was based not only on geomorphological and oceanographic parameters but also on sociological. The coasts of the Peloponnese peninsula are highly indented, as are the coasts of the Primorje-Gorski Kotar County (PGC) and other parts of the coast of the Republic of Croatia. The aim of the study was to assess the overall (physical and social) vulnerability of the Peloponnese peninsula to coastal erosion and flooding due to climate change. The assessment is based on the calculation of the coastal vulnerability index (CVI) and the social vulnerability index (SVI). The use of a quantitatively derived social vulnerability index is important as the method provides a useful tool for comparing the spatial variability of social vulnerability using a single value derived from multi-criteria characteristics. The SVI can be linked (statistically and spatially) to several physically based indices to calculate the overall vulnerability of a given location. This index not only makes an important contribution to the methods and scales used in vulnerability research, but also provides important information for spatial planning and emergency services.

Due to predicted climate change, research to assess the vulnerability of coastal areas has increased (Lima and Bonetti, 2020). Vulnerability studies are now conducted frequently and regularly in the European Union and worldwide. In contrast, coastal vulnerability studies in the Republic of Croatia are relatively rare and occasional, despite the total length of the coastline of more than 6000 km, its importance for the economy and the pressure created by the growth of tourism (ETC CCA, 2011; Pikelj et al., 2018). However, none of the existing formulations of CVI are applicable to steep and indented coastlines, as they mostly focus on coastal flooding.

The first analyses of the vulnerability of Croatian coastal areas using the Gornitz methodology were carried out in the coastal area of Šibenik-Knin County (Berlengi et al., 2016; Trumbić, 2011). In PGC, however, the first studies were based on analyses of local coastal erosion and instability. Most studies were conducted on the southeast coast of the Krk Island, near Stara Baška, where marine erosion occurs. The problem of coastal vulnerability in this area has been described in several studies over the last 30 years (Fig. 2-g) (Benac, 1992; Juračić et al., 2009; Ružić et al., 2018, 2015, 2014; Ružić and Benac, 2016). Stara Baška is one of the few places in the PGC where the erosion-related changes can be confirmed by comparing the orthophotos available in the Geoportal of the State Geodetic Administration. This is not the case for most of the coastal area, as the changes are small in relation to the scale of the orthophotos. The vulnerability of the coast near Stara Baška and the geological hazard posed by the expected sea level rise have recently been studied in detail (Ružić et al., 2021, 2019). The complex coastal morphology and geology as well as the pronounced coastal erosion in some parts of the investigated area called for an adaptation of the existing CVI approaches. The importance of the geological setting for the CVI calculation was particularly emphasised.

This study proposes an improved CVI assessment methodology for the rocky coastline over 1200 km long, whose geological fabric, morphological and oceanographic features change on a small scale. It describes a modification of the original vulnerability methodology that is better suited to describe the steep, indented, predominantly carbonate Croatian coastline. The novelty of this research lies in the fact that coastal slope is associated with rockfalls and landslides (from cliffs), since the instabilities of cliffs pose great risks for infrastructure and people, while inundation depends on the elevation of the coast. The CVI was calculated for almost 50,000 coastal cross-sections, for every 25 m of the total 1200 km of coastline, taking into account morphological features, geological fabric, wave heights, potential inundation and the presence of beaches. Due to the characteristics and length of the investigated coastline, the novel CVI approach had to be developed. A new formulation for the cumulative value of the CVI was tested, which emphasizes the positive influence of beaches. Similar formulations can be applied to other rocky coastlines. The results of the project are also available online on the geoportal of Primorje-Gorski Kotar County, where statistical indicators with the values of the determined coastal vulnerability index and its sub-indices are presented interactively.

2. Study site

Croatia occupies a central portion of the Mediterranean coastline, positioned along the eastern shores of the Adriatic Sea (Fig. 1-a and b). The territory of Primorje-Gorski Kotar County, situated in the northwest of the Croatian coastal region, provides a representative illustration of the broader Adriatic coastal features, reflecting the region's intricate geological and maritime characteristics. The marine area of the PGC, with an area of 4344 km^2, makes up 55 % of the total area and includes a large part of the Kvarner area (Public Institution The Institute for Physical Planning of Primorje-Gorski Kotar County, 2021).

The eastern coast of the Adriatic Sea is the *locus typicus* of the "Dalmatian coast", a type of submerged karst relief. It is a drowned mountainous coast consisting of parallel fold ranges, resulting in zigzag channels that run parallel and normal to the general coastal trend. Therefore, the northeastern coast of the Kvarner area and the island chains of Cres-Lošinj and Krk-Rab-Pag have a "Dinaric" direction of extension (NW-SE). The eastern coast of the Istrian peninsula, on the other hand, is oriented NNE-SSW (Fig. 1). These island chains divide the Kvarner area into smaller marine basins: Rijeka Bay, Kvarnerić, Kvarner and the Vinodol-Velebit Channel (Fig. 1-c).

There are 110 Natura 2000 sites in the PGC, covering 74.89 % of the

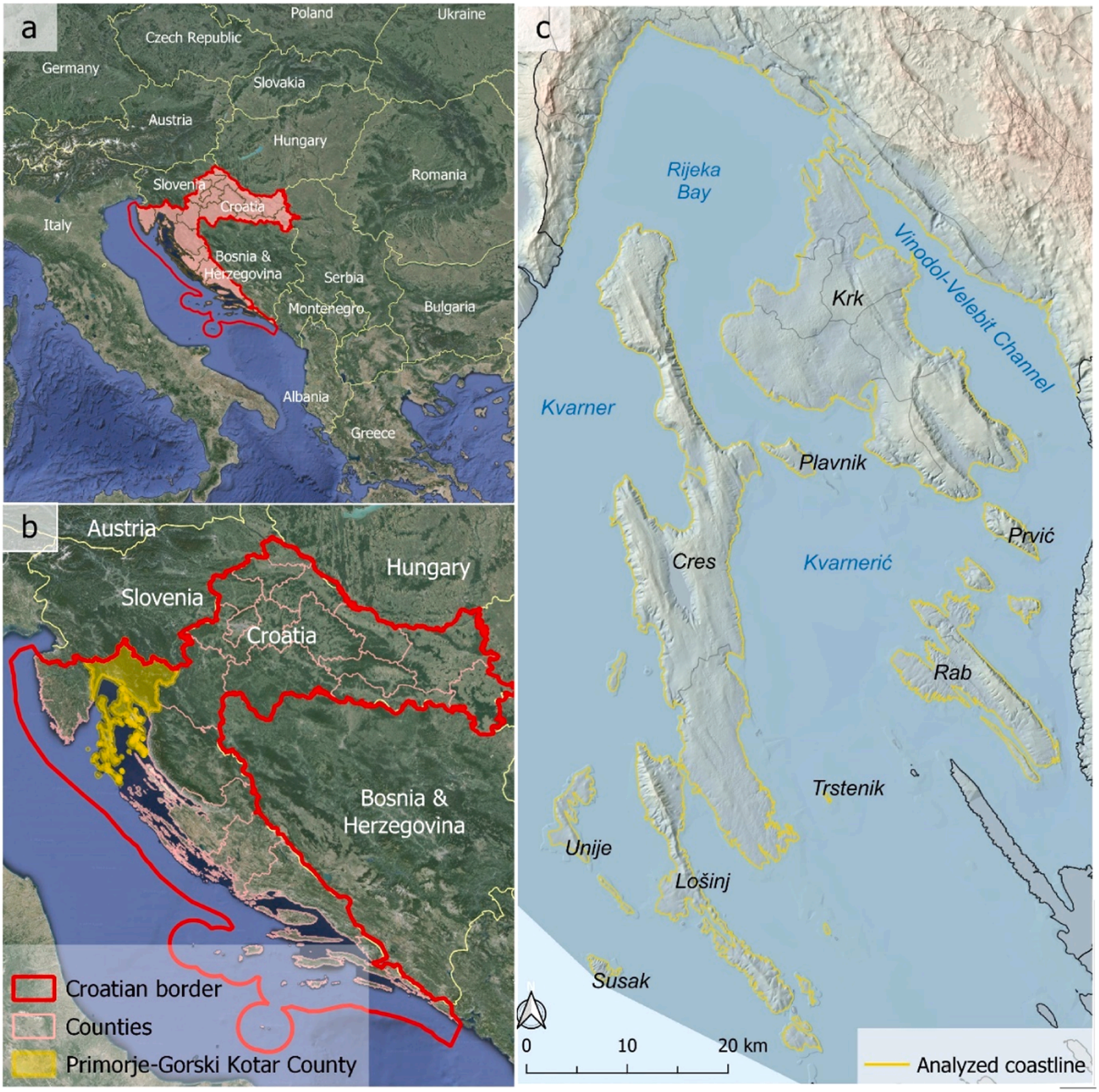


Fig. 1. Location of: **a.** Rebublic of Croatia; **b.**Primorje-Gorski Kotar County; **c:** coastal and island territory of Primorje-Gorski Kotar County.

land area and 16.36 % of the marine area. The spatial distribution of mean annual and mean seasonal precipitation is very complex because of the complex orography. Annual rainfall ranges from 2668 mm in the mountainous part to 869 mm on south coast (Jurić et al., 2016).

A large part of the very steep to vertical coastal sections in Primorje-Gorski Kotar County are tectonically predisposed. Only a small part are cliffs, i.e. scarps formed by marine erosion. However, similar instability phenomena occur on both morphogenetic coastal types, i.e. rockfalls and rock debris. For this reason, the term cliff is generally used in the text of this paper.

2.1. Geological fabric

Intense morphogenetic processes during Pliocene, Pleistocene and Holocene caused by tectonic movements and rapid sea level oscillation, as well as climatic changes, have created the present shape of the relief of the Kvarner area (Benac and Juračić, 1998).

In the terrestrial part of the Kvarner area, Cretaceous carbonate sedimentary rocks (limestones, dolomites and carbonate breccia), Palaeogene limestones and carbonate breccia as well as Palaeogene siliciclastic rocks or flysch (mostly marls, siltstones and sandstones in alternation) are present (Croatian Geological Survey, 2009). Carbonate rocks prevail, whereas siliciclastic outcrops only occur to a small extent. Pleistocene and Holocene cohesive and non-cohesive sediments (terra rossa, loess, proluvium and alluvium) partially cover the bedrock.

On the seafloor of the Kvarner area three main seabed geological types are found: bare rocky bottom, bottom covered with coarse-grained sediments (sandy gravel and pebble) and bottom covered with fine-grained sediments (sand and mud) (Juračić et al., 1999). Gravel beach bodies are partly found on carbonate rock coasts, while most of the coasts formed in flysch are covered by sand beaches (Juračić et al., 2009).

2.2. Oceanographic characteristics

The marine area of the PGC is strongly influenced by the meteorological, oceanographic and hydrological conditions that prevail in the wider area. In addition, the direction and size of waves and sea currents, as well as the seasonal and annual fluctuations in temperature and salinity, are significantly influenced by the described separation of the water area by island chains and the relatively narrow passages between them (Fig. 2).

The wave climate is determined by the winds (direction, duration and intensity) and the developed morphology of the coast and seabed. Waves from the northeast are the most frequent, followed by waves from the southeast, which are the highest due to the largest fetch. Waves from

Fig. 2. Coastal zone of Primorje-Gorski Kotar County with a position of tide-gauge in Bakar (red star) and examples of coastal vulnerability: a – c coastal flooding in Rab (RabDanas, 2019), Rijeka and Cres (Novi list, 2020); d – wave overtopping in Volosko (Opatija city); e – g rockfalls and landslides in Crikvenica, St. Marko Island, Stara Baška (Krk); h – damage of the promenade in Čikat Bay (Lošinj Island).

the west and southwest are relatively rare but can be important for the design parameters of coastal structures such as seawalls, breakwaters and ports.

The maximum astronomical tidal amplitudes in Kvarner are about 80 cm and are more pronounced compared to the central and southern Adriatic (Vilibić et al., 2017). The tides are the only deterministic periodic movements of seawater and can be accurately predicted for a location over the long term. The almost completely regular course of the tides is interrupted by fluctuations in the sea level due to changes in atmospheric influences. A rise in air pressure associated with northerly winds lowers the sea level in the northern part by up to 40 cm, while a drop in air pressure associated with southerly winds raises the level by up to 100 cm (Međugorac et al., 2015). As a result of sudden changes in air pressure and wind, free fluctuations in the water level occur, known as storm surges. Extremely high storm surges are also called meteo-tsunamis. This phenomenon is particularly pronounced when the occurrence of tides, wind waves, and the movement of water masses towards the shallow coast are coordinated (Penzar et al., 2001). High tides or *acqua alta* is the term used to describe the occurrence of extremely high tides in the Adriatic Sea, which peak in the Venice lagoon and have also been observed at several locations in the northern Adriatic (Fig. 2a – c). In the last fifteen years, record-breaking sea levels have also been measured in the Kvarner region. At the tide gauge in Bakar, the level was 117 cm above mean sea level on December 1, 2008, 122 cm on November 1, 2012 and it was 127 cm on November 1, 2018 (Međugorac et al., 2022, 2021). Data from tide gauges show that higher sea levels occur more frequently, which indicates an accelerated sea level rise. Sea level prediction is an important factor in coastal vulnerability analysis, as well as in spatial planning of coastal zones, as it affects the infrastructure and landscape. The vertical movements follow the horizontal advances of the water, i.e. the tidal waves (currents). Estimates of average sea level rise along the Croatian coast range from 0.32 m to 0.65 m by the year 2100, with more recent estimates reaching 1.1 m (Republic of Croatia, 2020). If the effects of storm surges are added, the extreme sea levels could reach 1.4 m to 2.2 m by the end of the 21st century (Orlić and Pasarić, 2013; Republic of Croatia, 2020). Sea level rise could be one of the costliest consequences of climate change on the Croatian coast in long-term scale (Perić and Šverko Grdić, 2015; Republic of Croatia, 2020).

The most obvious effect of sea level rise is coastal flooding. Low-lying parts of the PGC coast (e.g. Rijeka, Cres, Mali Lošinj, Rab, Vinodolski) are already flooded by higher tides and southerly winds (Fig. 2a – c). On the other hand, areas protected by seawalls struggle with wave overtopping (Fig. 2d), which can cause damage to coastal infrastructure (Fig. 2h). Seawalls often protect the roads, so the resulting splashing can endanger traffic (Fig. 3a). Wave activity can also lead to scouring of coastal roads, as was observed in Baška (Krk Island). The constant overtopping and scouring of the Palada Street (Fig. 3b) were eventually solved with groynes and beaches filled in between them. Beaches dissipate the wave energy on their bodies, thus reducing the potential vulnerability of a location (Pantusa et al., 2022; Ružić et al., 2019). The positive effects of the built-up beaches are described in more detail in the work of Capić (2005).

Along the coast of the PGC there are also many natural beaches that have formed below the cliffs and whose sediment comes from the erosion of the cliff slopes. The beach-cliff systems are in a very delicate balance, with occasional rockfalls occurring along the coast (Fig. 2e - g). However, the balance of the beach-cliff system is disturbed in some places by urbanization on the top of the cliff. Examples of this are Pećine near Rijeka (Ružić et al., 2022) and Havišće Bay near the town of Crikvenica (Fig. 2e; Ružić et al. 2024). Geotechnical measures were implemented at these two locations to prevent the cliff erosion. This led to an acceleration of beach erosion and consequently to the erosion of the cliff, endangering the infrastructure and buildings above. Wave action and erodibility, which depends on the degree of fissuring and weathering, are the main factors for cliff retreat (Sunamura, 1995). Wave action can reduce the stability of cliffs and coastal scarps. As a result, debris and rockfall processes increase. This accretion of sediment increases the thickness of the beach body and thus the protection of the foot of the cliff. However, if these new sediments can be eroded by waves and long-shore currents, the abrasive effect and the erosion rates of the cliff and marine terraces increase (Kennedy and Milkins, 2015; Komar and Shih, 1993; Moses and Robinson, 2011). Slight changes in the shape or elevation of the relief in the nearshore and foreshore zone can significantly alter the rate of cliff retreat (Lee, 2008).

3. Methodology

This study presents the methodology for refining the Coastal Vulnerability Index (CVI) assessment tailored to the complex coastal characteristics of the predominantly carbonate Croatian coast.

The total length of the coastline on which the analyses were carried out is 1194 km – the entire coastline on the mainland, and 22 islands, with the island of Trstenik being the smallest analysed element with an area of 0.35 km^2. The digital elevation model (DEM) of the study area had a resolution of 25 m and was provided by the State Geodetic Administration (DGU). The bathymetry used for the numerical simulation of waves was derived from the digital model of the seabed (DGU, 2019) and available bathymetric survey data. The starting point for the following analyses is the coastline defined as part of the international project to monitor changes along the coastline (PAP/RAC, 2019).

The first methodological step in CVI assessment concerns the definition of key variables that represent the processes influencing the vulnerability of coastal areas (Gornitz et al., 1997; Gornitz and White, 1992). The selection of variables that are representative for a specific coastal area is usually based on the available data related to the characteristics of the research area. The second step concerns the analysis and quantification of key variables with corresponding sub-indices. Although different methods may be available for this step, quantification is generally based on the definition of semi-quantitative outcomes on a scale from 1 to 5 (Gornitz, 1991; Thieler and Hammar-Klose, 1999): 1 means a low impact on the vulnerability of the area under study, while

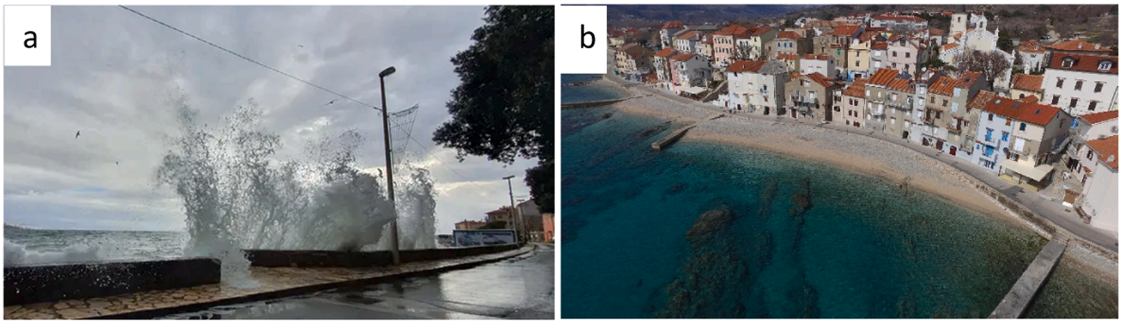


Fig. 3. a: splashing of the waves in Volosko near Opatija city (24sata, 2020); **b**: beaches in Baška (Krk Island).

5 indicates a high impact.

In this study, the coastal vulnerability index was defined based on five variables related to geological fabric, coastal slope, coastal flooding, impact of the beach (natural features of the coast), and wave action (forces acting on the coast). Some of the analyses performed had to be adapted to the research area, in relation to the original parameters mentioned in other analyses described in the Introduction, due to the different characteristics of the researched area. The rules to assigning the vulnerability sub-indices are shown in Table 1.

The ***geological fabric (a)*** largely determines the coastal vulnerability in heterogeneous coastal areas such as the PGC coastal area. Geomorphological features express the relative erodibility of different soil types and require data on their spatial distribution as well as their stability. They are presented in sub-indices geological fabric and coastal slope (Table 1). The geological map was taken from the Spatial Planning Information System of PGC and supplemented with unpublished new data (Fig. 4a).

Taking into account the relief features, geological fabric or lithological composition and the effects of geomorphological processes, as well as the purpose of this study and the scale of the graphical representation, the studied coastal area can be divided into four following basic types, which are also listed in Table 1:

- the coasts composed of carbonate rocks are defined with a very low vulnerability (1)
- the coasts composed of flysch rocks are defined as moderately vulnerable (3)
- the coasts composed of coarse-grain sediments (coarse gravel and cobble with different proportion of sand) are defined with high vulnerability (4)
- the coasts composed of fine-grained sediments of loess (silty sand), terra rossa (silty clay) and alluvium (mixed coarse sand and silty sand) defined with very high vulnerability (5).

In most studies (e.g. (Boumboulis et al., 2021; Gornitz, 1991; Kantamaneni et al., 2018; Koroglu et al., 2019; Mafi-Gholami et al., 2019; Özyurt and Ergin, 2010; Pantusa et al., 2022, 2018), the ***coastal slope (b)*** is considered from the perspective of coastal inundation for existing and projected sea levels. As sea level rises, coastline retreat will primarily occur in low coastal areas with a slope of up to 2 %. However, erosion and a significant retreat of the coastline may also occur on steep (rocky) coasts (Ružić et al., 2019, 2015, 2014; Trenhaile, 2018a, 2018b). Since the largest part of the PGC coastline is steep, the vulnerability (stability) of coastal slopes was also analysed, where an increase in coastal slope reduces stability against sliding, overturning and landslides, i.e. increases vulnerability. Therefore, the vulnerability of the PGC coastal area to the parameter of coastal slope is defined in terms of slope stability. In this paper, based on available data from DEM for the study area, coastal slope is calculated at a distance of 25 m from the coastline and ranges from a few degrees on the beaches to very steep or vertical cliffs. This parameter is sensitive to the scale of the DEM, so more detailed data is required to analyse the potentially vulnerable areas. The stability of steep coasts (cliffs) depends on many factors, such as geological structure, slope, groundwater, waves, vegetation, sediment talus, etc. Coastal vulnerability is defined for more resistant carbonate rocks and less resistant flysch and loess formations in combination with coastal slopes (Table 1). The classification presented is based on relevant local studies, available geological maps and the author's experience (Croatian Geological Survey, 2009; Mamužić et al., 1969; Šikić et al., 1969; Šušnjar et al., 1970).

The ***significant wave height – H_s (c)*** relevant for the CVI assessment is defined on the basis of numerical simulations of waves at a distance of 25 m from the coastline. The wave simulations were performed using the numerical model Simulating Waves Nearshore (SWAN). The third-generation numerical model for coastal applications, SWAN, is based on the Eulerian formulation of the equilibrium equation of spectral wave action (Booij et al., 1999; Holthuijsen et al., 2003). In this paper, numerical simulations were carried out for several directions for a 50-year return period, with the predominant directions being NE and SE (Fig. 5). The input wind parameters were taken from various studies on wind-wave climate of the region (Lončar et al., 2014). The simulations are based on a field of constant wind strength with a 50-year return period and were performed up to the coast for mean sea level.

The impact of the simulated significant wave height on coastal vulnerability is divided into five vulnerability categories (Table 1). The simulated waves are transformed due to variations in coastal topography. The simulated wave height at 25 m from the coast was taken as a representative value for the coastal vulnerability due to the numerical scheme, the input bathymetry and the coastal topography.

As already mentioned, vulnerability to coastal flooding in the literature is usually indicated by a gentle slope of the terrain. Here we have determined the categories of vulnerability based on the elevation of the terrain behind the coastline (Table 1).

The ***coastal flooding (d)*** variable was defined as very high if the coastal elevation at a distance of 25 m from the coast was lower than 1.30 m, which corresponds to a coastal slope of 5 %. That is also the value (1.27 m) of the highest tide recorded on the Bakar gauge, as mentioned above. Similar extreme tides were determined by a field survey at several locations. Low vulnerability was defined on the coast at elevations above 5 m, which corresponds to a coastal slope of 20 %. To account for the projected sea level rise (SLR) of 0.60 m, the thresholds for the coastal flooding variable have been adjusted accordingly. The classification intervals have been increased by 60 cm, which ensures that the increased vulnerability due to higher sea levels is accurately represented in the analysis.

Beaches (e) are a natural system resistant to the action of waves and usually have a low vulnerability. When analyzing the vulnerability of the coastal area, the parameter width of the beach is usually used (ETC CCA, 2011; Pantusa et al., 2022). This is a parameter related to the ability to dissipate wave energy on the beach body (Earlie et al., 2018; Lee, 2008). By absorbing the energy of breaking waves, beaches reduce unfavourable coastal processes. In previous studies carried out in PGC (Ružić et al., 2019), the value of the coastal vulnerability index is very low on beaches wider than 15 m. A width of 10 – 15 m results in a low coastal vulnerability index, 5 – 10 m in a moderate one, 2.5 – 5 m in a high one, and 0 – 2.5 m in a very high one.

While recent studies have utilized satellite imagery to measure beach changes (e.g. Mishra et al., 2021, 2023), determining the width of beaches across the PGC area from the available maps was not possible due to the scale of the available maps and the majority of small pocket

Table 1
Definition of vulnerability classes: sub-indices and cumulative CVI.

Vulnerability (CVI)		Very low (1)	Low (2)	Moderate (3)	High (4)	Very high (5)
a - geological fabric		Carbonate rocks		Flysch	Sediments: Gravel, Cobble	Sediments: Sand, Silt, Clay Loess
b - coastal slope [°]	Carbonate rocks	0–11.99	12–19.99	20–31.99	32–69.99	70–90
	Flysch and loess	-	0–4.99	5–11.99	12–19.99	20–90
c - significant wave height, Hs [m]		0–0.99	1–1.49	1.5–1.99	2–2.49	≥ 2.5
d - coastal flooding [m]		≥ 5	3.5–4.99	2.3–3.49	1.3–2.29	0–1.29
Cumulative CVI		0–1.79	1.8–2.19	2.2–2.61	2.6–3.07	3.1–4.2

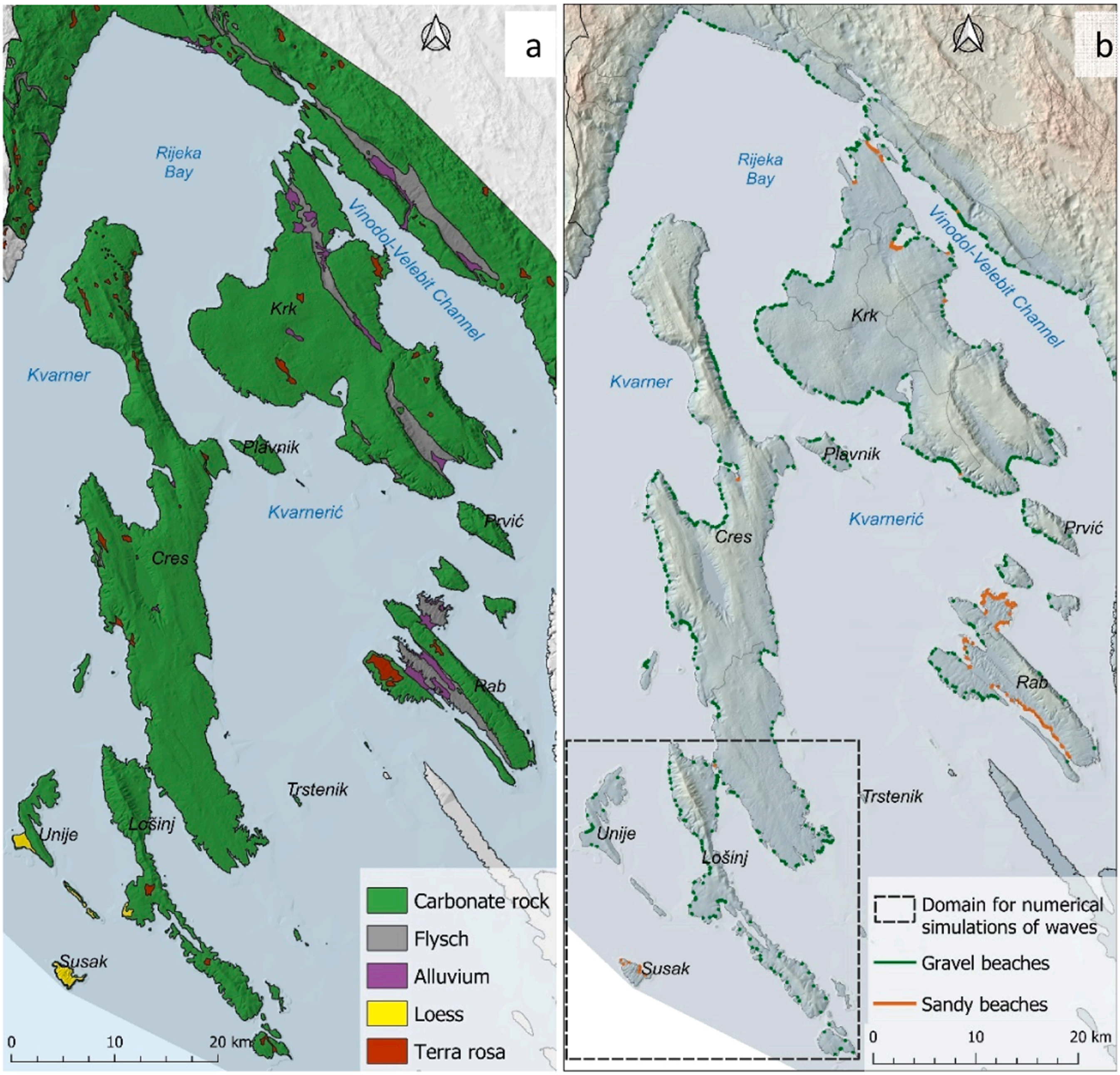


Fig. 4. a. Simplified geological map of the coastal and island part of Primorje-Gorski Kotar County; **b.** beaches in the PGC and domain for wave simulations around Lošinj (an example).

beaches (Fig. 4b). Therefore, the variable of beach width was simplified according to the *presence and type of beaches* with negative sub-indices, as shown in Table 2. Gravel and pebble beaches are more resilient than sandy beaches, which is why they reduce coastal vulnerability more (Table 2). A detailed analysis of the influence of beaches on coastal vulnerability should be based on a more detailed scale (LiDAR data) when it will be possible to define the beach width.

Finally, the key variables are integrated into a single index. Gornitz and White (1992) and Gornitz et al. (1997) proposed and tested different formulas (considering 7 key variables) to derive the final CVI:

$$\text{Product mean} CVI_1 = \frac{x_1 \bullet x_2 \bullet x_3 \bullet x_4 \bullet \ldots \bullet x_n}{n} \tag{1}$$

$$\text{Modified product mean} CVI_2 = \frac{x_1 \bullet x_2 \bullet 0,5(x_3 \bullet x_4) \bullet x_5 \bullet 0,5(x_6 \bullet x_7)}{n-2} \tag{2}$$

$$\text{Average sum of squares} CVI_3 = \frac{x_1^2 + x_2^2 + x_3^2 + x_4^2 + \quad \ldots + x_n^2}{n} \tag{3}$$

$$\text{Modified product mean(2)} CVI_4 = \frac{x_1 \bullet x_2 \bullet x_3 \bullet x_4 \bullet \ldots \bullet x_n}{5^{(n-4)}} \tag{4}$$

$$\text{Square root of product mean} CVI_5 = \sqrt{\frac{x_1 \bullet x_2 \bullet x_3 \bullet x_4 \bullet \ldots \bullet x_n}{n}} \tag{5}$$

$$\text{Sum of products} CVI_6 = 4x_1 + 4x_2 + 2(x_3 + x_4) + 4x_5 + 2(x_6 + x_7) \tag{6}$$

where: n = the number of variables; x_1 = mean elevation; x_2 = local

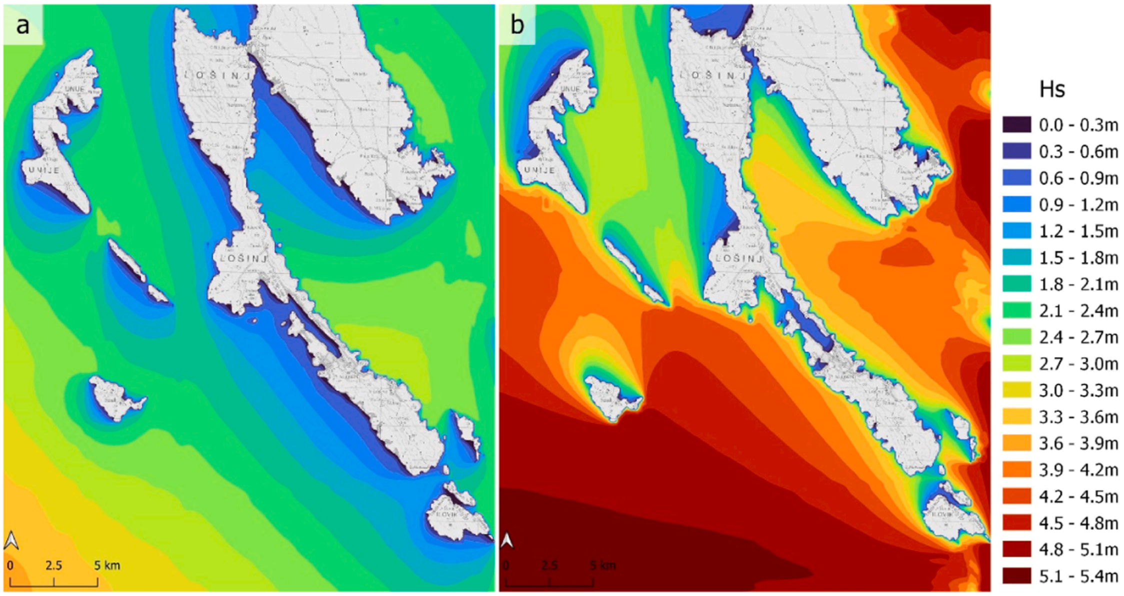


Fig. 5. Numerical wave simulations for Lošinj Island and southern part of Cres Island, including small islands: Unije, Vele and Male Srakane, Susak and Ilovik (domain in Fig. 4b): a. NE wind of 50-year return period, b. SE wind of 50-year return period.

Table 2
Coastal vulnerability – effect of beaches.

Beach	Vulnerability (e)
Gravel and pebble	- 2
Sand	- 1

subsidence trend; x_3 = geology; x_4 = geomorphology; x_5 = mean shoreline displacement; x_6 = maximum wave height; x_7 = mean tidal range.

Based on the previously described partial indices of vulnerability for the PGC coastal belt, several of these formulas were tested to determine total CVI. However, this paper defines the final CVI according to the following formula, with a negative sign accounting for the positive effect of the beach (*e*) on the overall coastal vulnerability:

$$\mathrm{CVI} = \sqrt{\frac{a^2 + b^2 + c^2 + d^2 - e^2}{5}}$$

The vulnerability intervals are shown in Table 1 and were obtained by adjusting the standard natural break (Jenks) classification using the QGIS tool (version 3.16.1) to ensure that the results obtained were consistent with the natural characteristics of the coasts in the Kvarner region. This adjustment was based on previous vulnerability studies in the Kvarner region (Ružić et al., 2019; Ružić and Benac, 2016), as well as on field trials conducted for the purposes of this project. The results obtained in this way are the most realistic for the coasts of the PGC. They are shown in the form of vulnerability maps, generated in QGIS.

Appropriate segmentation of the coastline under study is an important step for vulnerability analyses. Too long segments cannot capture the significant variations at smaller distances (Tsaimou et al., 2023). Due to the (geomorphological) complexity of the PGC coastal area, vulnerability was analysed point by point, every 25 m of the coastline. The analyses were performed for each of the 47,560 points on the coast and their respective cross sections perpendicular to the coastline.

4. Results

The average value of the coastal vulnerability sub-index for the geological fabric parameter (*a*) is 1.31, which means very low vulnerability and is due to the favourable geological structure of most of the coastline (88.9 %). Only 4.5 % (54 km) of the coastline is highly and very highly vulnerable. The vulnerability map is shown on the left part of the Fig. 6.

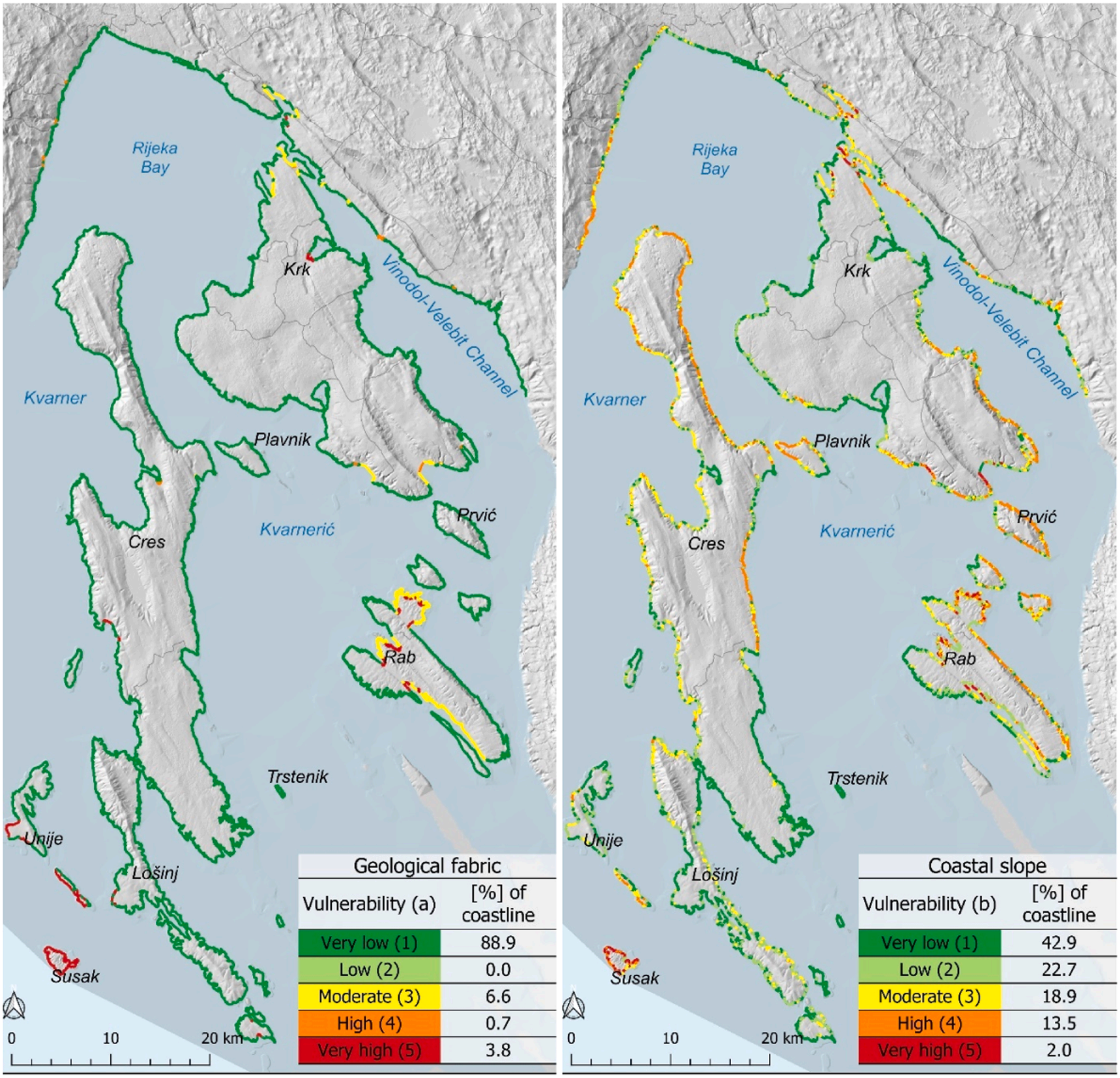
The average value of the CVI in relation to the coastal slope at the PGC level is 2.09, which represents a relatively low vulnerability and is the result of the prevailing favourable combination of slope and geological structure of the coast. However, 185 km (15.5 %) of the coastline is highly and very highly vulnerable. The most vulnerable is the coastal area of Susak (Fig. 6, right), where unfavourable coastal slopes are formed on an unfavourable geological fabric of flysch and loess.

The average CVI value for wave action (Fig. 7, left) is 1.95, which represents a low vulnerability. Around one-eighth of the coastline (148 km) is exposed to the direct impact of high waves, which corresponds to a high to very high vulnerability. In these locations, the waves have significant adverse effects on the coast itself; they can trigger coastal erosion, wave overtopping and splashing can occur even at higher elevations (up to 5 m), and the salt can also significantly accelerate corrosion.

The results of coastal flooding must be considered in the context of the vertical (in)accuracy of the available terrain models. Almost two-thirds (65 %) of the PGC coastline is of low and very low vulnerability to flooding, but over 24 % (291 km) of the coastline is of very high and high vulnerability, which is of great concern. The risk of flooding is present in the entire area of PGC, and additionally unfavourable is the fact that most coastal settlements are exposed to this risk (Fig. 8, right). This coincides with the frequent negative consequences in the area, where most coastal settlements are flooding during extremely high sea levels (Fig. 2).

With the expected rise in sea level, the vulnerability of the PGC coastline will increase considerably. In the case of a sea level rise of 0.60 m, the proportion of coastal areas classified with low and very low vulnerability is expected to decrease by 4.8 %, while the proportion of coastal areas with very high vulnerability will increase by 5.1 %. These figures are even less favourable for extreme sea levels associated with storm surges.

Based on the performed analysis of the individual vulnerability sub-indices and the defined formula, the aggregated CVI was determined. Several analyses were performed using different CVI formulas, but a formula was selected that emphasises the reduction in vulnerability due



Geological fabric	
Vulnerability (a)	[%] of coastline
Very low (1)	88.9
Low (2)	0.0
Moderate (3)	6.6
High (4)	0.7
Very high (5)	3.8

Coastal slope	
Vulnerability (b)	[%] of coastline
Very low (1)	42.9
Low (2)	22.7
Moderate (3)	18.9
High (4)	13.5
Very high (5)	2.0

Fig. 6. Vulnerability maps in relation to geological fabric (left) and coastal slope (right), with the respective proportions of sub-indices in the total length of the coastline.

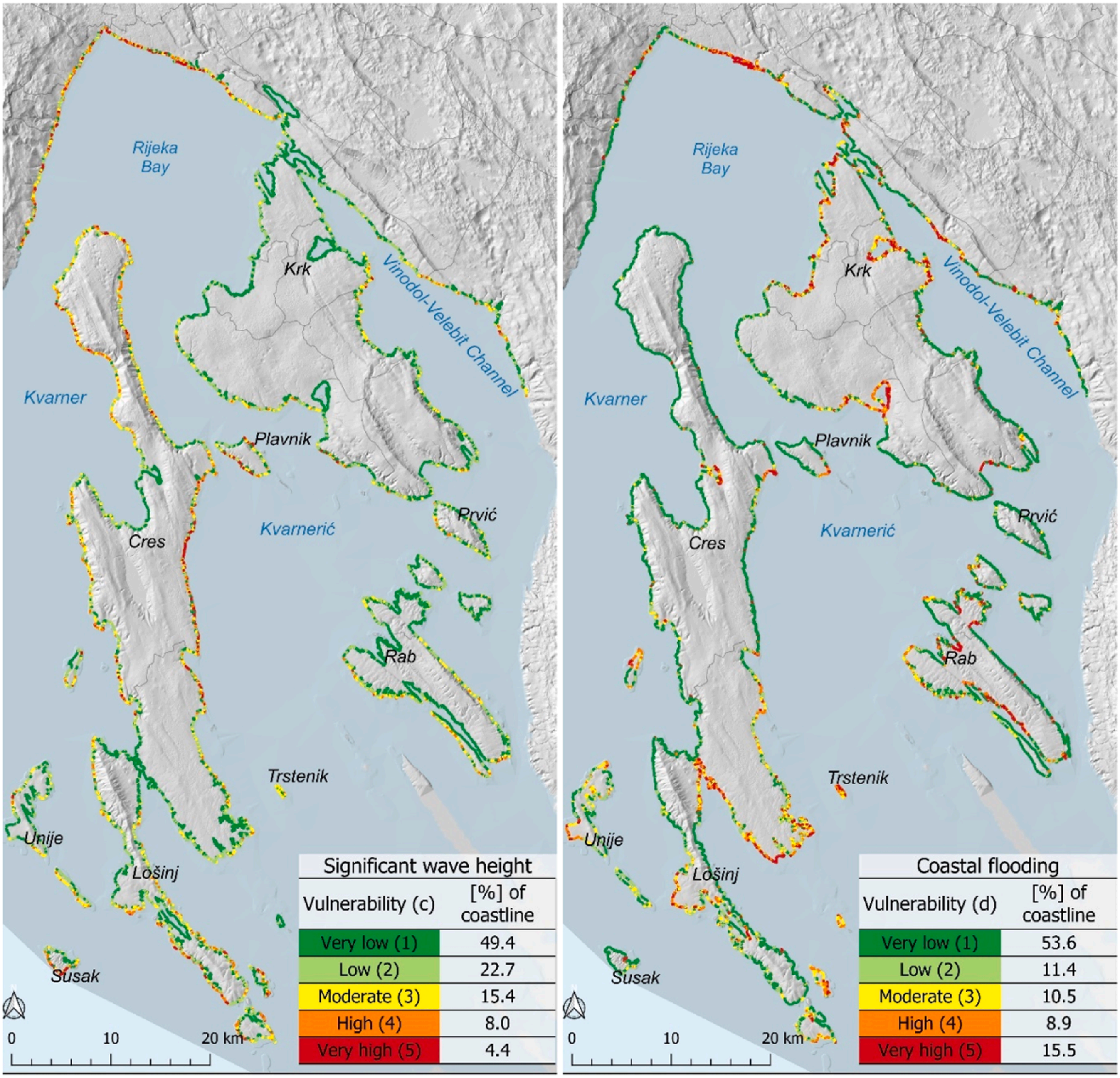
to the presence of beaches. The majority of PGC coastal zone (805 km or 67.4 %) has low to very low vulnerability, while 13 % have high to very high vulnerability. The average vulnerability is 2.02, which corresponds to a low vulnerability.

The most vulnerable is the Susak Island, whose entire coastline has a CVI of 4 or 5. The largely uninhabited southern part of the Cres Island is classified with moderate to high vulnerability due to its low-lying shores and exposure to wave action. The Rab Island generally has a high CVI with an average value of 2.63. It is characterised by a coastline that is mostly not vulnerable, but 33 % (48 km) of its coastline is highly and very highly vulnerable. On the Rab Island, this is aggravated by the fact that the built-up areas coincide with the most vulnerable areas, which significantly increases the risk.

5. Discussion

In this study, the vulnerability of the coastal area of PGC was investigated by a simple method of assessing coastal vulnerability index (CVI), which is composed of several partial indices (sub-indices). Although the method itself is generally simple, the analysis of the variables defining the vulnerability can be very complex, especially in the studied area of indented coastline with a total length of 1200 kilometres, an inhomogeneous geological structure and lithological cover, extremely inhomogeneous wave fields, a large number of different beach types and sizes, a large number of different settlements, etc. For this reason, certain adjustments had to be made to the vulnerability parameters commonly used.

The commonly used variables – relative SLR and mean tide range, were not analysed in this paper. The distance between the northernmost



Significant wave height	
Vulnerability (c)	[%] of coastline
Very low (1)	49.4
Low (2)	22.7
Moderate (3)	15.4
High (4)	8.0
Very high (5)	4.4

Coastal flooding	
Vulnerability (d)	[%] of coastline
Very low (1)	53.6
Low (2)	11.4
Moderate (3)	10.5
High (4)	8.9
Very high (5)	15.5

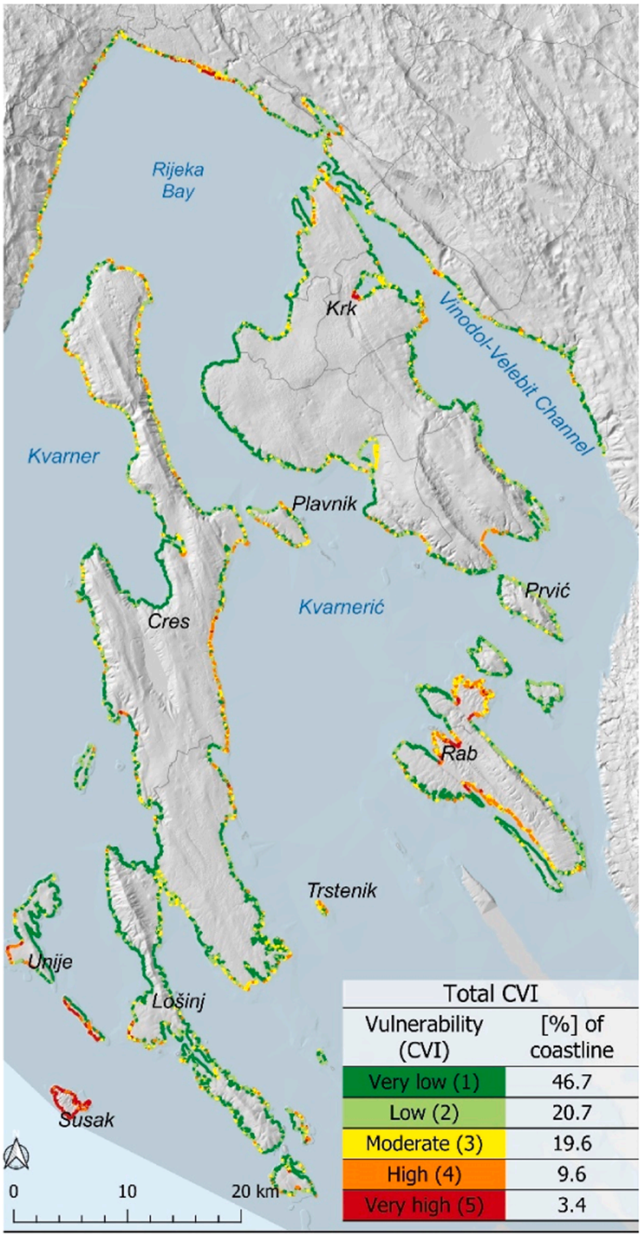
Fig. 7. Vulnerability maps in relation to significant wave height (**left**) and coastal flooding (**right**), with the respective proportions of sub-indices in the total length of the coastline.

and southernmost point of the investigated area is only about 100 km, so the relative differences in sea level cannot be significant. Furthermore, there is only one tide gauge station – the Bakar station – with a sufficiently long measurement series to obtain reliable data (Međugorac et al., 2022; Šepić et al., 2022). Only recently a larger number of stations with a favourable spatial distribution have been established from which this parameter can be analysed, especially the influence of storm surges. The same was done in Tsaimou et al. (2023)

The parameter of shoreline change, i.e. the rate of coastline erosion/accretion, could not be analysed due to a lack of data. Namely, there is no reliable data on the change of the coastline in the entire study area, only data for certain smaller areas (as described above for Stara Baška coastal area), which can only be used for local analysis. However, there are no major shoreline changes in the PGC area, as most of the coastline is made of resistant limestone and changes are local and rare. The largest changes in the coastline position may have occurred on the gentler slopes due to erosion or sediment deposition, but these changes are very difficult to quantify. The use of orthophoto imagery to analyse coastal changes is difficult, for example, due to the high slopes on gravel beaches.

The coastal relief of the studied area is very complex, the coastline is indented and has complex cross-sections, so the analyses of the vulnerability of the coastal area in relation to the coastal slope must be carried out in accordance with the scale used. Given the available data, the coastal slope was defined from a DEM with a resolution of 25 m, which is too coarse a scale for a quality analysis of the stability of critical slopes. To analyse such areas, detailed surveys using LiDAR or SfM photogrammetry are required.

A major limitation is the availability of geodata, which ranges in scale from 1: 5,000 for orthophotos and topographic maps to 1: 25000



Total CVI

Vulnerability (CVI)	[%] of coastline
Very low (1)	46.7
Low (2)	20.7
Moderate (3)	19.6
High (4)	9.6
Very high (5)	3.4

Fig. 8. Vulnerability map of the total CVI, with the proportions of indices in the total length of the coastline.

digital elevation models (DEM). The scale problem in the analyses performed is mainly reflected in vertical accuracy and the large distance between the points of the DEM (25 m) in often very steep terrain, which can affect the accuracy of the analyses performed, especially when the results of the vulnerability analysis are also projected to the area beyond the coastline (e.g. when defining the inundation limit of the coastal area for certain sea level rise scenarios). This was also the conclusion of Apostolopoulos and Nikolakopoulos (2020), who examined the position of the coastline using statistical analysis and satellite imagery. They found that low resolution data is not suitable for proper mapping and analysis as the accuracy is very low. Similar problems with the accuracy of the maps and their scope are also mentioned in other similar studies for the territory of the Republic of Croatia (Berlengi et al., 2016; UNDP, 2009). For this reason, the objectives of this study are adapted to the mentioned limitations, so the aim is to identify potentially vulnerable areas of PGC, which will be analysed in detail in the possible continuations of this project, or it is recommended to perform a detailed analysis on appropriate detailed maps.

The results have also shown that smaller islands (Fig. 9) are particularly vulnerable to SLR, which is in accordance with Newton and Weichselgartner (2014). Due to their geometric characteristics and low elevations, even small SLR causes large loss of relative surface area.

The maps presented here can further be used for land use planning. For example, when considering the construction of new infrastructure with a design life of several decades, it is preferable to choose an area with a lower CVI, regardless of other considerations (e.g. the economic or environmental benefits of a particular location) and future improvements in the understanding of changes in coastal hazards (Le Cozannet et al., 2013).

In exposed areas, it is not advisable to build coastal structures (breakwaters, artificial beach, coastal wall, etc.) without first carrying out appropriate studies and analyses. It is extremely important to maintain a certain distance from the sea. Rising sea level, new storm waves and extreme weather events must be taken into account when planning construction.

The impact of beaches on the vulnerability of rocky shores (most of the PGC) is very complex. For an adequate understanding of the influence of beaches on cliffs, rocky scarps and man-made structures, it is important to know when beach sediment is abrasive, which is a combination of beach profile shape, sediment size, tides and waves (Kennedy and Milkins, 2015). There is a lack of research on such effects, which can only be analysed using products from detailed geodetic measurements (LiDAR, UAV-SfM). For this reason, this paper simplifies the impacts of beaches on CVI to just two variables, representing sand and gravel beaches, with a focus on the need to perform additional analyses for vulnerable areas. Since beaches are present on the coasts of Primorje-Gorski Kotar County only to a small extent, the reduction in coastal vulnerability due to the previously described positive effects of beaches is low.

This vulnerability assessment is only a starting point for a proper risk analysis and ultimately for the adoption of adaptation measures. The next steps must be interdisciplinary (Bukvic et al., 2020; Ciccarelli et al., 2017; Yang and Kim, 2023). The costs of (flood) protection are generally very high, so the question arises as to who will bear these costs.

6. Conclusion

This paper analyses the vulnerability of the indented coastal area of the Primorje-Gorski Kotar County in Croatia. Detailed analyses of five representative variables and the overall coastal vulnerability index were performed at every 25 m of the coastline with a total length of 1200 km in 48,000 points. The presented approach is suitable for coastal vulnerability analysis of complex rocky coasts. The conducted analysis required an original approach and the application of new technologies for the calculations of coastal vulnerability. The calculation of most of the variables required the development of new methods and formulas for their determination due to the specificity of the research area and the available data.

The results of the collective CVI show that a small part of the PGC coast is at risk, although the negative influence of the individual variables considered should not be ignored. Potentially endangered coastal areas of the PGC were identified.

The CVI calculation presented prioritises the geological setting in combination with the coastal slope as the most important factor for adverse coastal change. This paper emphasises the impact of coastal landslides and rockfalls on coastal vulnerability, which are not considered in the vast majority of similar analyses.

The influence of wave action on CVI was defined from the results of numerical wave modelling for a point 25 m offshore from the base point. This approach adequately accounts for the impact of high-impact and low probability events on coastal vulnerability. In this way, the actual wave impact can be determined for the complex coastline, taking into account that Hs values vary from 0.24 m in sheltered locations to 6.86 m

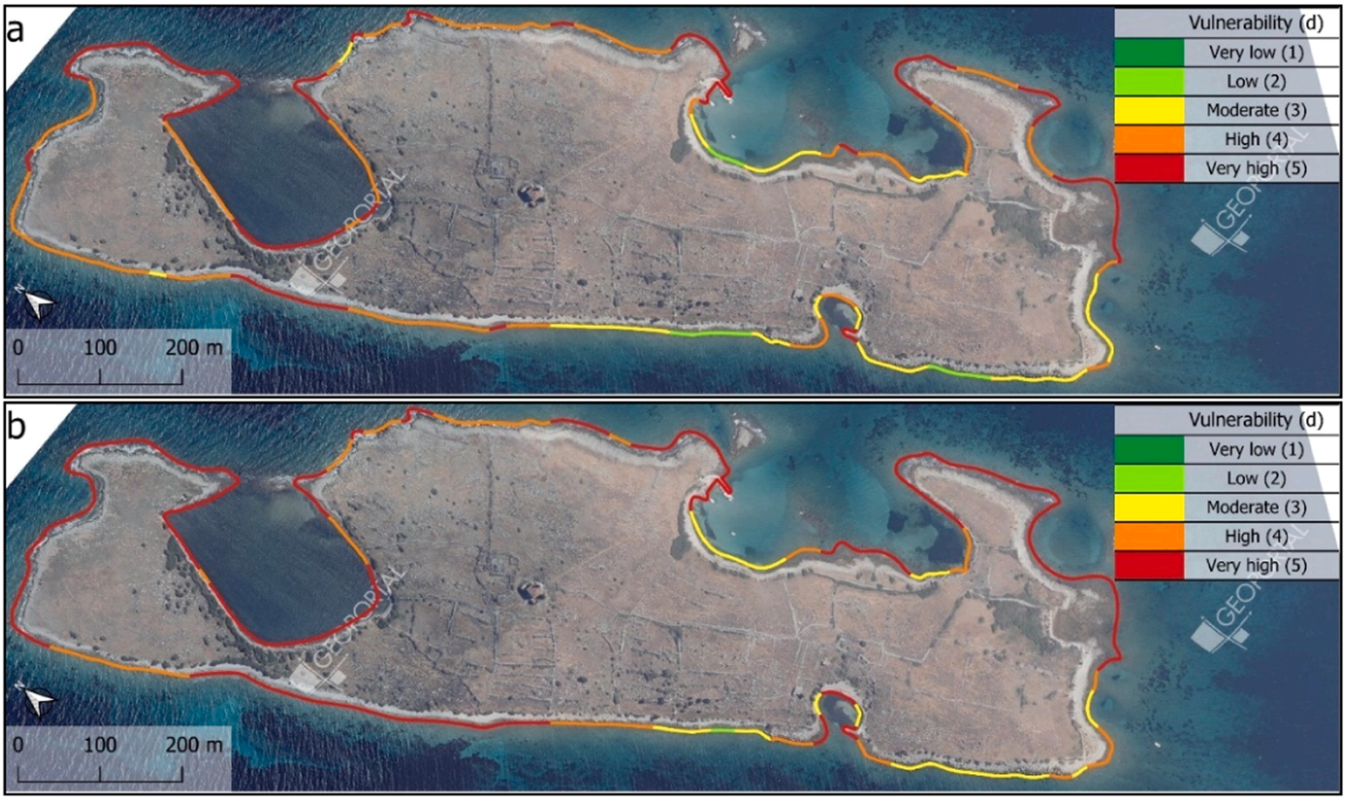


Fig. 9. The Trstenik Island – vulnerability for the coastal flooding: a. for present high tides, b. for predicted SLR of 60 cm.

on outer islands.

A quarter of the coast (291 km, 24 %) is at risk of flooding, which is worrying and indicates that this problem needs to be addressed and solved. If the sea level were to rise by 60 cm, the current percentage of the vulnerable coast would increase to around 30 %.

Smaller islands and islets are particularly vulnerable to the expected changes, especially in relation to their area and length of coastline. Fortunately, most of these islands are not at high risk as they are either not yet developed and populated or only small structures such as piers or lighthouses have been built.

The island of Susak, parts of the islands of Vele and Male Srakane and Unije are the most vulnerable areas of the PGC due to a combination of unfavourable geological structure, wave action, terrain slope and coastal flooding. The vulnerability of these islands needs to be further investigated.

Adequate vulnerability analyses are many times more complex, so in addition to a more accurate geological foundation and terrain model, the effects of waves, especially the range of their impact and the effects on the terrain, must be analysed in detail. The aim of this study was to identify potentially vulnerable areas of PGC, which will be analysed in detail in the possible continuations of this project. This study provides a decision-making tool for the development of coastal areas under the influence of climate change, which is extremely important given the increasing pressure on coastal areas, especially due to the development of tourism.

CRediT authorship contribution statement

Andrea Tadić: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Igor Ružić:** Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Čedomir Benac:** Supervision, Methodology, Investigation, Funding acquisition, Formal analysis. **Nino Krvavica:** Writing – original draft, Methodology, Funding acquisition, Formal analysis.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Author agreement statement

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We understand that the Corresponding Author is the sole contact for the Editorial process. He is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

Data Availability

Data will be made available on request.

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